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## Hydrothermal fluid paths in continental margin

**Hydrothermal fluid flow system around the Iheya North Knoll in the****mid-Okinawa Trough based on seismic reflection data**

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***Research Highlights (4 bullet points)***

*(1) Possible fluid flow paths in the Iheya North Knoll hydrothermal field*

*(2) Widespread permeable volcanic deposits produced by silicic arc volcanism*

*(3) Layered sequence focuses migration of fluids derived from trough-fill sediments*

*(4) Fluid alteration accelerated by interactions with sediments*

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24    **Abstract**

25    **Seismic reflection data around the Iheya North Knoll hydrothermal field provide**  
26    **insights into geological structures that control subseafloor hydrothermal fluid flow**  
27    **in the sediment-covered continental backarc basin of the mid-Okinawa Trough.**  
28    **We identified the seismic expression of widespread porous volcanoclastic**  
29    **pumiceous deposits and intrusions as a result of silicic arc volcanism. The porous**  
30    **and permeable volcanic deposits distribute in an area extending updip from the**  
31    **thick succession of the deep trough to the seafloor at the hydrothermal field. Their**  
32    **regional structure focuses the flow of hydrothermal fluids derived from the**  
33    **surrounding trough-fill sediments and directs them to the vents of the**  
34    **hydrothermal field. The high concentrations of CH<sub>4</sub> and NH<sub>4</sub> in the fluids of the**  
35    **hydrothermal field are likely derived from the interaction of migrating fluids with**  
36    **trough-fill sediments.**

37

38    **Keywords:** Hydrothermal fluid paths, Okinawa Trough, seismic reflection data,  
39    continental backarc basin, silicic volcanism

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**1. Introduction**

The circulation of hydrothermal fluids enhances chemical and thermal exchange and the interaction between the crust and ocean (e.g., Stein and Stein, 1992). Because of the considerable influence of hydrothermal fluid circulation within oceanic lithosphere on the physical, chemical, and biological evolution of the crust and ocean, it has been well studied at spreading axes and on their flanks (e.g., Fisher et al., 1997; Fisher, 1998; Johnson et al., 2000; Fisher et al., 2003; Hutnak et al., 2008; Fisher et al., 2008; Waldhauser and Tolstoy, 2011; Fisher et al., 2011). In contrast, there have been few studies of hydrothermal fluid circulation in subduction zones, such as at island arc submarine volcanoes and in continental backarc basins. Because backarc basins at continental margins are usually covered by thick sequences of terrigenous sediments, an understanding of fluid recharge and migration paths cannot be obtained only from near-seafloor observations.

The hydrothermal field on Iheya North Knoll, about 150 km NNW of Okinawa Island, was discovered in 1995 (Fig. 1; Momma et al., 1996) and has since been investigated during more than 40 dives of manned deep submergence vehicles (DSVs) and remotely operated vehicles (ROVs). These investigations have demonstrated that prosperous subseafloor microbial communities associated with the hydrothermal fluid



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60 chemistry are hosted along the entire hydrothermal fluid flow path, from sedimentary  
61 pore water to hydrothermal discharge zones (Nakagawa et al., 2005; Takai et al., 2006).  
62 The chemistry of the hydrothermal fluids in the Okinawa Trough (a backarc basin) is  
63 unusual among deep-sea hydrothermal fluids studied to date (Ishibashi and Urabe,  
64 1995; Gamo et al., 2006; Takai et al., 2006; Takai and Nakamura, 2010; Kawagucci et  
65 al., 2011). High concentrations of CO<sub>2</sub> and CH<sub>4</sub> are common in fluids in hydrothermal  
66 systems underlying sedimentary sequences, such as at the Juan de Fuca Ridge (Lilley et  
67 al., 1993; Shanks et al., 1995) and in the Guaymas Basin (Welhan and Lupton, 1987;  
68 Pearson et al., 2005). However, the concentrations of CO<sub>2</sub> and other gaseous carbon  
69 compounds in hydrothermal fluids from the Okinawa Trough are among the highest in  
70 the world (Gamo, 1995; Konno et al., 2006; Takai and Nakamura, 2010; Kawagucci et  
71 al., 2011). Most of these volatiles are likely derived from subseafloor interactions  
72 between sediments and infiltrated seawater (Kawagucci et al., 2011). In addition, vent  
73 fluids from Okinawa Trough hydrothermal systems have high concentrations of Ba,  
74 provided by hydrothermal reactions between felsic volcanic rocks and hydrothermal  
75 fluids (Gamo et al., 2006). Despite the unusual fluid chemistry of the Okinawa Trough  
76 hydrothermal systems, there has been little investigation of their geological and  
77 hydrogeological setting. Understanding the hydrogeology of hydrothermal systems is of

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fundamental importance in studying the interactions among geological, geochemical, and microbial processes in the deep-sea hydrothermal environment of a continental backarc basin. In this study, we investigated the structure of the hydrothermal fluid flow system of the Iheya North Knoll hydrothermal field on the basis of our interpretation of a dense grid of seismic reflection data covering the Iheya North Knoll.

### 2. Geologic setting

The Okinawa Trough lies in the eastern East China Sea, between the Ryukyu Arc – Trench system and the Eurasian continent (Fig. 1a). In this area, the Okinawa Trough is considered to be in the initial stage of continental rifting, although there is some argument on the commencement and order of the Okinawa Trough rifting (e.g., Letouzey and Kimura, 1985). Most previous studies suggest that rifting commenced in the southern part of the trough (e.g., Sibuet et al., 1995; Hsu et al., 2001) and that it started at ~2 Ma. The Yangtze River is the main source of the thick terrigenous sediments that cover the crust of the mid-Okinawa Trough (Narita et al., 1990; Huh and Su, 1999), where the sedimentation rate has been estimated to be 1–2 m ka<sup>-1</sup> (Tsugaru et al., 1991).

The Iheya North Knoll is on the northern termination of the depression of the

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96 Okinawa Trough (27.8°N, 126.9°E; Fig. 1) where water depths are greater than 1000 m.  
97 The volcanic body of the Iheya North Knoll penetrates through a thick sedimentary  
98 sequence and rises about 500 m above the seafloor. The hydrothermal field lies on the  
99 eastern flank of the western peak of the knoll, facing the central valley (Fig. 1c). Several  
100 hydrothermal mounds have been recognized during previous surveys (e.g., Takai et al.,  
101 2006; Takai and Nakamura, 2010). They are clearly shown in high-resolution  
102 bathymetric data (Fig. 2) obtained by autonomous underwater vehicle (AUV) *Urashima*  
103 equipped with acoustic sounding equipment (SeaBat7125, 400 Hz source) during cruise  
104 YK07-07. The hydrothermal mounds are aligned roughly N–S (Fig. 2).

105 The highest temperatures (maximum 311 °C) and highest hydrothermal flow rates  
106 have been recorded at the vent known as North Big Chimney (NBC; Fig. 2) over a  
107 period of more than ten years (e.g., Kawagucci et al., 2011), indicating that the  
108 hydrothermal fluid vented from NBC comes from the main hydrothermal flow path in  
109 this region. The high temperature of discharged fluid (~300 °C) at NBC suggests a  
110 magma-driven system. Both temperatures and flow rates of other vents in the area  
111 decrease with increasing distance from NBC (Masaki et al., 2011). Furthermore,  
112 intensive hydrothermal plumes have been imaged by side-scan sonar in seawater only  
113 around the hydrothermal field (Kumagai et al., 2010).

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Recent Integrated Ocean Drilling Program (IODP), conducting a series of drill holes in the central valley of the Iheya North Knoll, showed that the sediments there are mainly pelagic and hemipelagic mud and volcanoclastic deposits (pumiceous gravels), and that they have been variably altered by hydrothermal processes (Expedition 331 Scientists, 2010). Drilling data revealed an alternating sequence of hard low-porosity layers and porous layers that were hydrothermally altered at high temperatures. The hard layers, presumably of low permeability, may provide the cap rock above hydrothermal fluid flow paths. The alignment of the active hydrothermal vents along the strike of the sedimentary layers (N–S; Fig. 2) suggests that the hydrothermal fluid flow paths are controlled by the layered sedimentary structures.

**3. Seismic data acquisition and processing**

We used 2D seismic reflection data acquired along 54 survey lines recorded in a dense orthogonal grid during four cruises (Table 1, Figs. 1b and 1c). Multi-channel seismic reflection data were recorded during cruises KY02-11, KY07-03, and KR10-02, and single-channel data during cruise YK06-09. During cruise KR10-02, long-offset (~4.5 km) multi-channel data were acquired in order to determine the velocity structure required to calculate depths of reflection events. A larger volume airgun was also used

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132 during cruise KR10-02 (Table 1).

133 The seismic data from cruises KY02-11 and KY07-03 were processed with a  
134 conventional processing sequence that included spherical divergence correction,  
135 deconvolution, common midpoint (CMP) sorting, normal moveout (NMO) correction,  
136 multiple suppression with a Radon filter, CMP stacking, migration, and bandpass  
137 filtering (Yilmaz, 2001). The short streamer deployed during cruises KY02-11 and  
138 KY07-03 (Table 1) did not allow estimation of accurate seismic interval velocities for  
139 deep reflectors. However, shallow geological structures were clearly imaged on these  
140 profiles (KY02-11 and KY07-03) and the single-channel data (KR06-09), because of  
141 the high resolution (high frequency) of the source signals used (Fig. 5).

142 To obtain accurate depths of subsurface geological structures for data from cruise  
143 KR10-02, we applied prestack depth migration incorporating an iterative horizon-based  
144 tomographic analysis of seismic velocity (see Figs. 3 and 4). We determined seismic  
145 velocities at six horizons, including the sediment–crust interface. Because the dominant  
146 frequency of the cruise KR10-02 data was lower than that of the other cruises, we used  
147 these data mainly for interpretation of the deep geological structure (Figs. 3 and 4).

148 Although 2D seismic reflection data do not unequivocally resolve structures in 3D  
149 (French, 1974), the dense grid of orthogonal profiles we used allowed us to identify the

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3D subseafloor structures with reasonable confidence. Furthermore, by comparing orthogonal profiles we were able to identify sideswipe reflections from nearby areas of elevated seafloor. Because the seismic interval velocities necessary for depth conversion could not be accurately determined within the knoll, we used 3D fence diagrams constructed from several time-domain reflection profiles (Fig. 6) to develop a representation of both subseafloor geological structures and possible hydrothermal fluid paths.

To interpret and characterize the subseafloor structures (e.g., volcanic deposits), we calculated seismic attributes (e.g., amplitude envelope; Fig. 7) (Taner et al., 1979; Tsuji et al., 2005). Magmatic intrusions can be imaged as blocks on the envelope profile (Fig. 7) mainly because the envelope ignores phase information; the intrusions disturb the original structure of sedimentary sequence (Tsuji et al., 2007).

### **4. Volcanic activity and pumiceous deposits**

The seismic profiles across the Iheya North Knoll reveal the subseafloor volcanic and sedimentary structures in the area under and surrounding the knoll. The subseafloor rocks of the Iheya North Knoll volcano are characterized by chaotic reflections that extrude through trough sediments of >1500 m thickness (Figs. 3 and 4). The depth of

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168 the seafloor around the knoll is greater on the southwestern side of the knoll (Figs. 3 and  
169 4) because of ongoing tectonic rifting in the Okinawa Trough. The seismic reflection  
170 profiles did not allow us to identify a heat source beneath the knoll because the  
171 complicated subsurface structure and steep seafloor terrain of the knoll made it difficult  
172 to resolve deep structures. The magma reservoir probably lies below the knoll at a depth  
173 beyond the resolution of our seismic data. However, southwest of the knoll we  
174 identified strong low-frequency reflectors beneath the trough sediments (~4 km below  
175 seafloor; red arrows in Fig. 4) that possibly represent a magmatic body. Numerous  
176 normal faults are developed in the sediments overlying the possible magmatic body and  
177 dip toward it (Fig. 4).

178 Some of the peaks of the Iheya North Knoll show intervals of low-amplitude  
179 reflections at and beneath the seafloor (Fig. 7a), including the peak east of the central  
180 valley (Fig. 5a). This seismic transparency indicates a lack of acoustic impedance  
181 contrast over these intervals, indicating that they represent intervals of homogeneous  
182 and porous rock. Piston cores obtained at the peak above the transparent interval during  
183 cruise KY08-01 (labeled A in Figs. 1c and 7a) are composed of volcanoclastic  
184 pumiceous deposits interbedded with silt (Oiwane et al., 2008), which would be  
185 expected to be seismically transparent. Thus, the transparent intervals likely represent

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186 volcaniclastic pumiceous deposits.

187 Pumiceous breccias are commonly observed within sediment cores obtained in and

188 around the Iheya North Knoll (Expedition 331 Scientists, 2010). In the central valley of

189 the Iheya North Knoll (the depression east of the hydrothermal field; Fig. 2), piston

190 cores revealed several pumice layers of ~10 cm thickness within 3 m below the seafloor

191 (labeled B in Figs. 1c and 5b) (Oiwane et al., 2008). On the eastern side of the knoll, a

192 volcaniclastic layer of about 40 cm thickness is interbedded within an approximately

193 5-m-thick sequence of mud-dominated trough sediments (labeled C in Fig. 1c). Our

194 seismic data cannot resolve such thin pumiceous layers (e.g., Rayleigh's criterion;

195 Sheriff, 2002). However, we noted high-amplitude reflectors extending horizontally

196 away from the Iheya North Knoll (white dashed lines in Fig. 7b), some of which are

197 discordant with the layered sedimentary sequence in the trough. These may represent

198 thick submarine volcaniclastic deposits, lava flows, or sills. Furthermore, a

199 low-frequency, high-amplitude reflection at the seafloor trace of a normal fault (gray

200 dashed line in Fig. 7c) may represent a magmatic body extruded on the seafloor after

201 upwelling via the normal fault. This observation also explains frequent intrusions

202 (complex network of volcanic deposits) within trough sediment.

203



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204 **5. Reservoir formation and hydrothermal fluid pathways**205 **5.1 Small-scale fluid circulation**

206 In the central valley of the Iheya North Knoll, there are repetitive east-dipping  
207 seismic reflectors within the sediments immediately below the seafloor (Fig. 5b),  
208 suggesting the existence of a layered sedimentary structure. Core samples demonstrate  
209 that the layered structure within this sedimentary sequence includes high-permeability  
210 pumiceous flow deposits (Oiwane et al., 2008; Expedition 331 Scientists, 2010). The  
211 permeability of the pumiceous gravels (Nakamura et al., 2008) obtained during drilling  
212 (Expedition 331 Scientists, 2010) was considerably higher than that of the  
213 mud-dominated pelagic sediments. Therefore, these highly permeable volcanic  
214 sequences might provide lateral migration pathways for pore fluids. Furthermore, the  
215 lateral distribution of high-permeability (pumiceous) layers overlain by  
216 low-permeability (pelagic and hemipelagic mud) layers may trap the fluid and provide  
217 reservoirs for subseafloor hydrothermal fluids. Whereas, this sedimentary sequence is  
218 also intersected by numerous steep normal faults, which might provide pathways for  
219 vertical (rather than lateral) flow of hydrothermal fluids.

220 Pyroclastic flow deposits may exist below the 200-m-thick layered sedimentary  
221 sequence that includes low-permeability mud, in the sequence between the black and

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222 gray diamonds in Fig. 5b. This porous, high-permeability sequence dips basinward from  
223 the volcanic body near the hydrothermal field, and may provide a path for hydrothermal  
224 fluids to migrate laterally up the slope. Furthermore, the N–S trend of the vents of the  
225 hydrothermal field at the western edge of the low-permeability central valley sediments  
226 (Fig. 2) corresponds to the trend of the seafloor outcrop of the pyroclastic deposits (Fig.  
227 5b), which supports the view that they may provide a conduit for hydrothermal fluid  
228 flow.

229 As one of the possible recharge entries around the central valley, a linear volcanic  
230 ridge located at ~2 km east of the hydrothermal vent sites (~30 m high and 500 m wide;  
231 Figs. 2, 5b and 8) is suggested on the basis of the heat flow measurements (*Masaki et al.*,  
232 2011). Numerous heat flow data in the region of the knoll have shown temperature  
233 increasing with depth, but heat flow data from the sediments on the volcanic ridge  
234 reveal an inverse gradient (*Masaki et al.*, 2011). Furthermore, the heat flow values  
235 increase gradually with distance from the ridge, reaching a maximum at the  
236 hydrothermal vents. The weak seafloor reflection of the volcanic ridge (Fig. 5b)  
237 suggests a porous volcanoclastic pumiceous seafloor there. Therefore, the ridge may  
238 provide an entry for recharge of hydrothermal fluids in the pyroclastic flow deposits  
239 beneath the central valley.

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If the volcanic ridge provides the primary hydrothermal fluid source at Iheya North Knoll, the hydrothermal fluid circulation cell is small, with only a few kilometers separating the main recharge and discharge areas (Fig. 5b). A circulation cell of this scale is comparable to those characteristic of fast-spreading mid-ocean ridges, where fluid residence times on the order of several to ten years have been estimated. A circulation cell of this scale would not sustain the steady hydrothermal fluid discharge, its chemistry, and the associating enormous chemosynthetic microbial and faunal communities of the Iheya North Knoll hydrothermal field (Nakagawa et al., 2005; Takai et al., 2006; Takai and Nakamura, 2010; Kawagucci et al., 2011). In particular, the carbon mass balance between hydrothermal fluid discharges and inorganic and organic carbon sources in the volcanic deposits and sediments within the Iheya Knoll structure clearly indicate that the hypothesized hydrothermal fluid paths could not support the CH<sub>4</sub> mass balance and stable isotope composition of the discharging hydrothermal fluids (Kawagucci et al., 2011). Thus, there must be other sources and pathways of hydrothermal fluids discharging at the Iheya North Knoll hydrothermal field.

**5.2 Large-scale fluid circulation**

On E–W seismic profile KY0703-18, we identified a strong west-dipping reflector

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258 beneath Iheya North Knoll, the eastern end of which approaches the seafloor near the  
259 hydrothermal vent sites (black circles in Fig. 5b). On the intersecting N–S seismic  
260 profile (KY0703-E), this strong reflector dips to the north away from the hydrothermal  
261 field (black circles in Fig. 5e). The high reflection amplitude (Fig. 5b) of this continuous  
262 reflector may represent an important boundary that controls hydrothermal fluid flow  
263 paths. The 3D structure of this reflector determined from our fence diagram of  
264 orthogonal seismic profiles (Fig. 6) indicates that it extends away from the knoll to the  
265 north and west, and that the shallowest part of the horizon converges on the  
266 hydrothermal field. Furthermore, we noted several reflectors below and parallel to the  
267 strong reflection, indicating a layered structures (gray circles in Figs. 5b and 5e). The  
268 polarity of the strong west-dipping reflector is opposite to that of the seafloor reflector  
269 (Fig. 5c), which indicates that the seismic velocity below the negative-polarity reflector  
270 is lower than that of the overlying sequence. DSV and ROV observations of the small  
271 peak immediately west of the hydrothermal field (e.g., NT07-11 cruise; Fig. 2) indicate  
272 that most of the seafloor there is paved with potential sheet carbonate crust containing  
273 numerous mussel shells and pieces of pumiceous breccia (Figs. 5b and 8). Based on the  
274 pumiceous volcanic structures exposed at the seafloor and the layered structures below  
275 and parallel to the negative-polarity reflector (gray circles in Fig. 5b), we interpret the

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276 negative-polarity reflector and underlying low-velocity sequence to represent porous  
277 volcanic breccia.

278 Because the permeability of the layered sequence underlying the negative-polarity  
279 horizon is likely higher than those above and below it, large-scale permeability  
280 anisotropy would be expected within the layered sequence; low-permeability sediments  
281 above the layered sequence would provide a cap structure to prevent vertical upward  
282 migration of fluids. Furthermore, as already pointed out, the shallow eastern extent of  
283 the negative-polarity reflector approaches the hydrothermal field (Fig. 6). Thus, we  
284 suggest that the layered sequence immediately below the negative-polarity reflector  
285 provides a major conduit that gathers hydrothermal fluids and channels them to their  
286 point of discharge at the Iheya North Knoll hydrothermal field.

287 The large number of dead mussel shells on the seafloor above the shallowest point  
288 of the negative-polarity reflector (Figs. 2, 5b, and 8) suggest that past methanotrophic  
289 mussel populations was sustained by considerable amounts of hydrothermally derived  
290 methane seepage. The seafloor reflector above the negative-polarity reflector is stronger  
291 than that of the surrounding seafloor (Fig. 5e), suggesting that a consolidated carbonate  
292 crust is exposed at the seafloor there. Although it is still unclear how old the mussel  
293 shells and carbonate crust are formed, the volatile components of the hydrothermal

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294 fluids such as CO<sub>2</sub> and CH<sub>4</sub> would escape from the hydrothermal reservoir by diffusion  
295 through the cap structure above the negative-polarity reflector, which may have been a  
296 less-effective seal in the past.

297 As shown by both the E-W and N-S seismic profiles, the negative-polarity event  
298 and underlying layered sequence extend into the thick trough-fill sediments that are  
299 widespread on the western and northern sides of the Iheya North Knoll (Figs. 5b and 5e).  
300 Considering the 3D structure of the negative-polarity horizon (Fig. 6), the large  
301 reservoir of pore water in the thick trough-fill sediments may provide the source of  
302 hydrothermal fluids, which then flow updip within the continuous permeable layered  
303 sequence before discharging at Iheya North Knoll hydrothermal field. Both the  
304 sedimentary sequence and the interbedded volcanic units were uplifted by the volcanic  
305 intrusion that formed the knoll. The resultant structure and the presence of a heat source  
306 beneath the knoll facilitate lateral migration of recharged fluids along the pumiceous  
307 layers toward the hydrothermal field. This conceptual hydrothermal system is consistent  
308 with the extraordinarily high concentrations of CH<sub>4</sub> and NH<sub>4</sub> in the hydrothermal fluids  
309 of the Iheya North Knoll hydrothermal field (Kawagucci et al., 2011). Rather, it is  
310 consistent with the prediction that the abundant CH<sub>4</sub> and NH<sub>4</sub> in the hydrothermal fluid  
311 should be derived from their reservoir in the more organics-rich, trough-filling

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312 sediments accumulated by subseafloor microbial methanogenesis and ammonification  
313 in certain geological time scales (Kawagucci et al., 2011).

314 We identified many normal faults within the trough-fill sediments around the Iheya  
315 North Knoll (Fig. 4). The major faults strike parallel to the trough axis (ENE–WSW).  
316 Although the lithology is the same on both sides of a major normal fault on line  
317 YK-0703-18, the reflection amplitude east of the fault is weaker than that west of the  
318 fault (Fig. 7b). If the normal fault creates a hydrogeological boundary to lateral flow,  
319 the higher amplitudes west of the fault might represent active hydrothermal fluid flow  
320 and/or gas trapped within sedimentary sequence near the knoll. On the other hand, these  
321 major normal faults extend from the seafloor to deep crustal basement (Figs. 3 and 4;  
322 Lee et al., 1980) and, if fluid flow is driven by thermal advection from the deep heat  
323 source beneath the Iheya North Knoll, it is also possible that these deep crustal faults  
324 provide vertical hydrothermal fluid migration paths (Fig. 8).

325

## 326 6. Discussion and conclusions

327 In the region of mid-ocean ridges, the primary conduits for hydrothermal fluids  
328 are highly permeable zones of upper oceanic crust and abyssal-hill faults (Fisher, 1998;  
329 Fisher and Becker, 2000; Fisher et al., 2008; Hutnak et al., 2008; Fisher et al., 2011).

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330 The thick sedimentary sequences that overlie basaltic crust on the flanks of mid-ocean  
331 ridges are generally considered to be impermeable to hydrothermal fluid flow. However,  
332 unlike the high-temperature fluids in sediment-hosted hydrothermal vent fields, the  
333 hydrothermal fluids there are not highly enriched with  $\text{CH}_4$  and  $\text{NH}_4$  (Wheat et al., 2003,  
334 2004). A plausible explanation for this difference is that the primary fluid source on the  
335 ridge flank is nutrient-poor oxygenated seawater recharged directly through volcanic  
336 outcrops on the seafloor (Fisher et al., 2003) such that the chemistry of the  
337 hydrothermal fluids is little affected by geochemical and microbiological alteration  
338 during migration.

339 The Iheya North Knoll hydrothermal system is part of a continental backarc basin  
340 where subseafloor silicic arc volcanic deposits provide complex migration networks for  
341 recharge and discharge of sediment pore fluids. Taking into consideration the  
342 extraordinary  $\text{CH}_4$  and  $\text{NH}_4$  enrichment of the fluids of the Iheya North Knoll  
343 hydrothermal field, there are four important components in the model we propose here  
344 for the hydrothermal fluid flow system.

- 345 1. The primary source of hydrothermal fluids is the nutrient-rich, reductive pore fluids  
346 of the trough-fill sediments around the Iheya North Knoll.
- 347 2. The primary fluid recharge and migration paths are through permeable trough-fill



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348 volcaniclastic sediments and normal faults that extend from the seafloor to crustal  
349 basement.

350 3. Geochemical and microbiological alteration of hydrothermal fluids passing through  
351 the complex network of flow paths enriches them in  $\text{CH}_4$  and  $\text{NH}_4$ .

352 4. The structural culmination around the knoll of the highly permeable volcaniclastic  
353 sequences that integrate multiple flow paths focuses fluid flow in the region of the  
354 hydrothermal vents.

355

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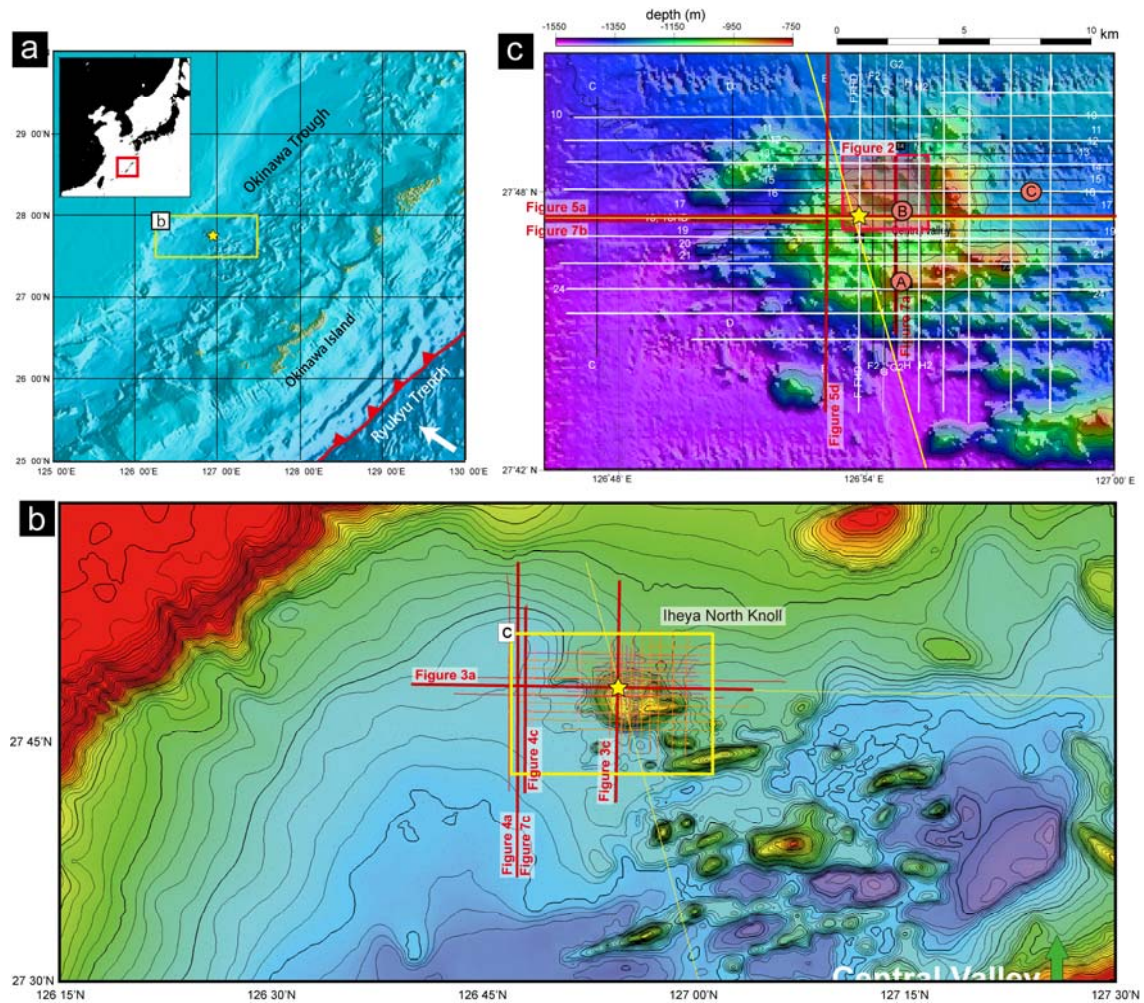
## Hydrothermal fluid paths in continental margin

**Table 1.** Acquisition parameters for seismic surveys

Cruise	Vessel	Survey lines	Streamer	Source
<b>KY02-11</b>	<i>R/V Kaiyo</i>	2 lines	24-channel, 600 m streamer	~2.5 L (150 inch <sup>3</sup> ) GI airgun
<b>YK06-09</b>	<i>R/V Yokosuka</i>	26 lines	1-channel Streamer	~2.5 L (150 inch <sup>3</sup> ) GI airgun
<b>KY07-03</b>	<i>R/V Kaiyo</i>	19 lines	48-channel, 1200 m streamer	~5.8 L (355 inch <sup>3</sup> ) GI airgun
<b>KR10-02</b>	<i>R/V Kairei</i>	7 lines	360-channel 4500 m streamer	~54 L (3300 inch <sup>3</sup> ) Tuned airgun

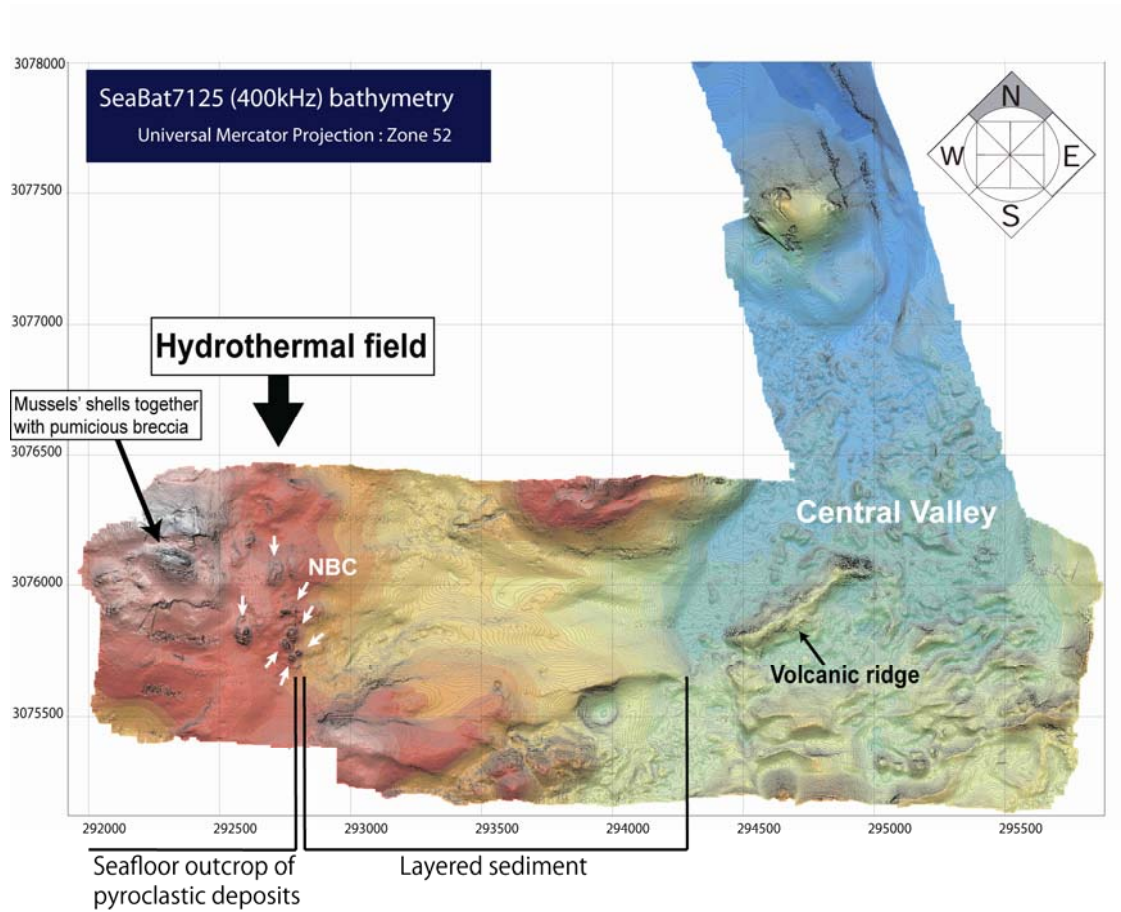
## Hydrothermal fluid paths in continental margin

### 524 Figure Captions



525 **Figure 1.** (a) Location map and bathymetry of the Okinawa Trough. (b)  
526 Bathymetric map of the Iheya North Knoll area showing seismic survey lines  
527 used in this study. The yellow star shows the location of the hydrothermal field.  
528 The seismic profiles displayed in Figures 3, 4, and 7 are shown as thick red lines.  
529 (c) Enlarged bathymetric map of the Iheya North Knoll area with seismic survey  
530 lines shown. The seismic profiles displayed in Figures 5 and 7 are shown as  
531 thick red lines.  
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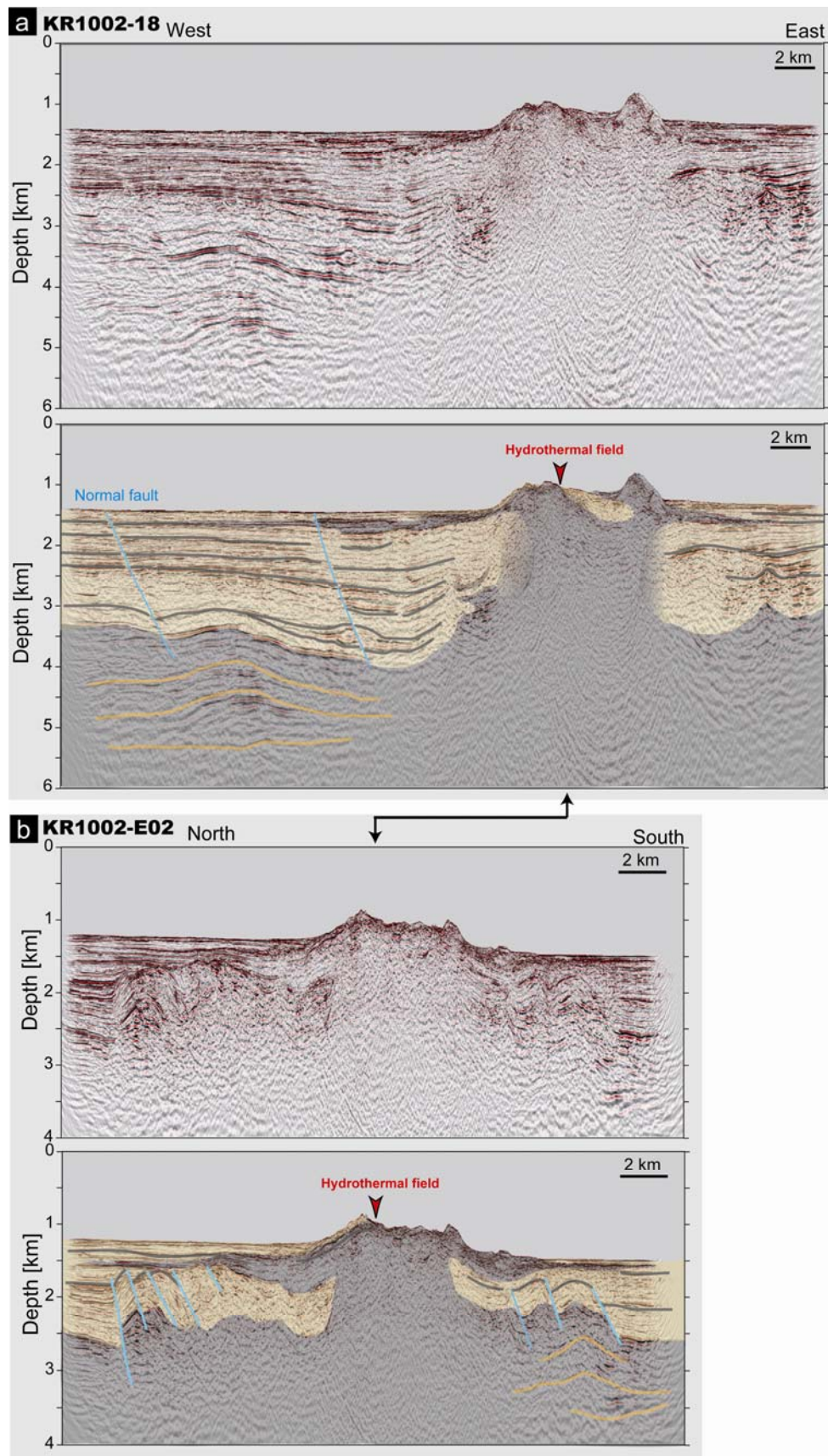
## Hydrothermal fluid paths in continental margin



**Figure 2.** Bathymetric map of the central valley within the Iheya North Knoll acquired by AUV *Urashima* during cruise YK07-07. White arrows indicate hydrothermal mounds. The volcanic ridge in the central valley and the peak on the western side of the hydrothermal field are also shown.



## Hydrothermal fluid paths in continental margin

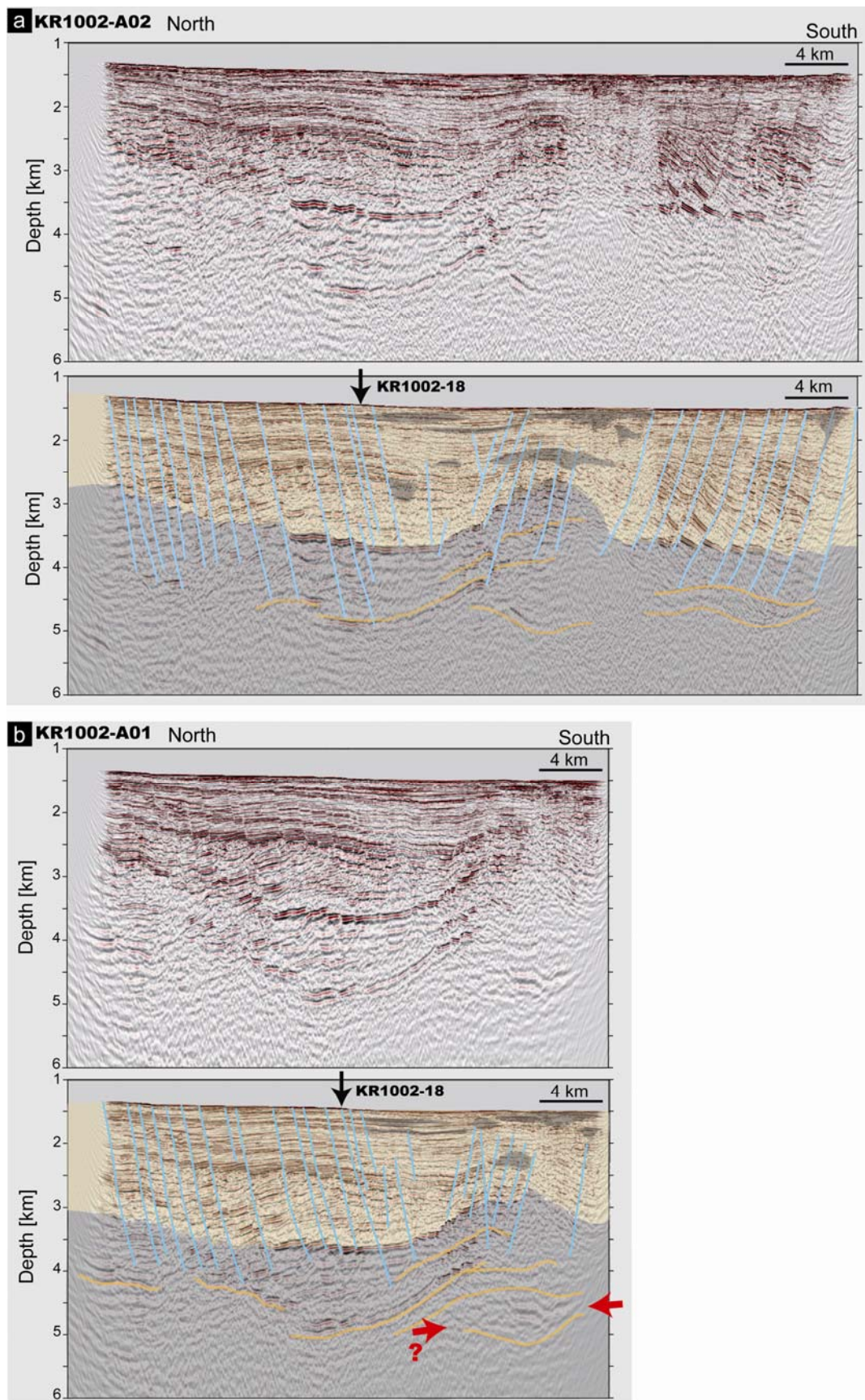


## Hydrothermal fluid paths in continental margin

540 **Figure 3.** Prestack depth migrated seismic profiles across the Iheya North Knoll  
541 hydrothermal field with and without geological interpretation. (a) E–W line  
542 KR1002-18 and (b) N–S line KR1002-E2. Locations of the profiles are shown in  
543 Figure 1b. The two profiles intersect at the Iheya North Knoll hydrothermal field  
544 (red arrow). Gray shaded areas indicate volcanic bodies or deposits with high  
545 permeability. Gray lines indicate geological boundaries, some of which are  
546 pumiceous deposits. The normal faults indicated by blue lines.



## Hydrothermal fluid paths in continental margin



## Hydrothermal fluid paths in continental margin

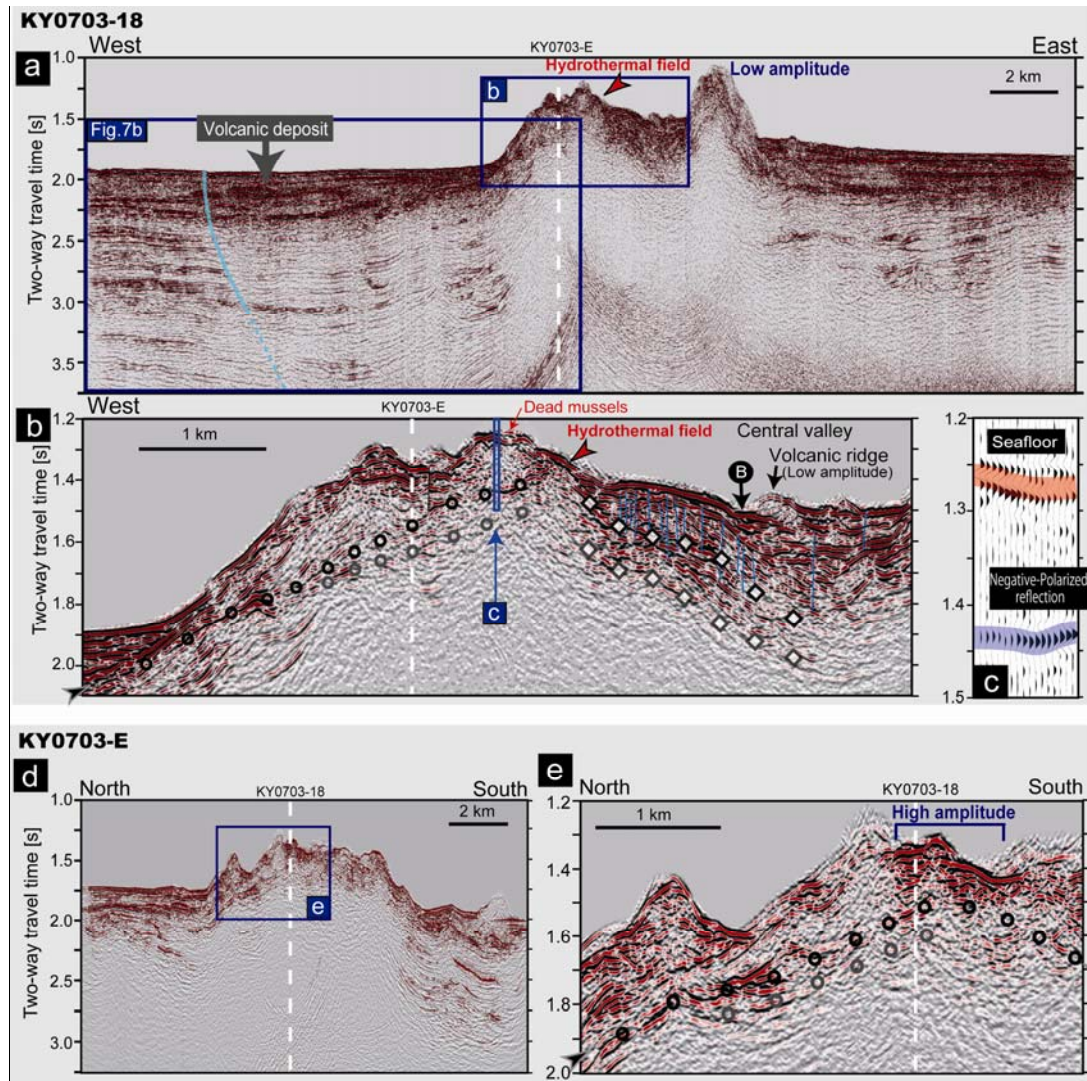
548 **Figure 4.** N–S prestack depth migrated seismic profiles (with and without  
549 geological interpretation) west of the Iheya North Knoll, showing intense normal  
550 faulting. (a) Line KR1002-A02 and (b) line KR1002-A01. Locations of the profiles  
551 are shown in Figure 1b. Normal faults (blue lines) may provide fluid recharge  
552 paths to the deep crust. Red arrows indicate the location of a possible magma  
553 chamber.

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## Hydrothermal fluid paths in continental margin



**Figure 5.** Interpreted time-domain seismic reflection profiles around the Iheya North Knoll hydrothermal field. Locations of the profiles are shown in Figure 1c. No amplitude gain control (AGC) was applied during processing of these sections. (a) E–W profile KY0703-18 and (d) N–S profile KY0703-E. Vertical white dashed lines indicate the intersection of the two profiles. Panels (b) and (e) show enlargements from profiles KY0703-18 and KY0703-E, respectively. Black circles indicate negative-polarity reflections. Gray circles indicate reflections

## Hydrothermal fluid paths in continental margin

564 parallel to the negative-polarity reflections. Black diamonds indicate the upper  
565 surface of pyroclastic flow deposits. Gray diamonds indicate the base of  
566 pyroclastic flow deposits. (c) Enlargement of panel (b) showing a seafloor  
567 reflection wavelet and a negative-polarity reflection. In panels (a) and (b), blue  
568 lines represent faults.

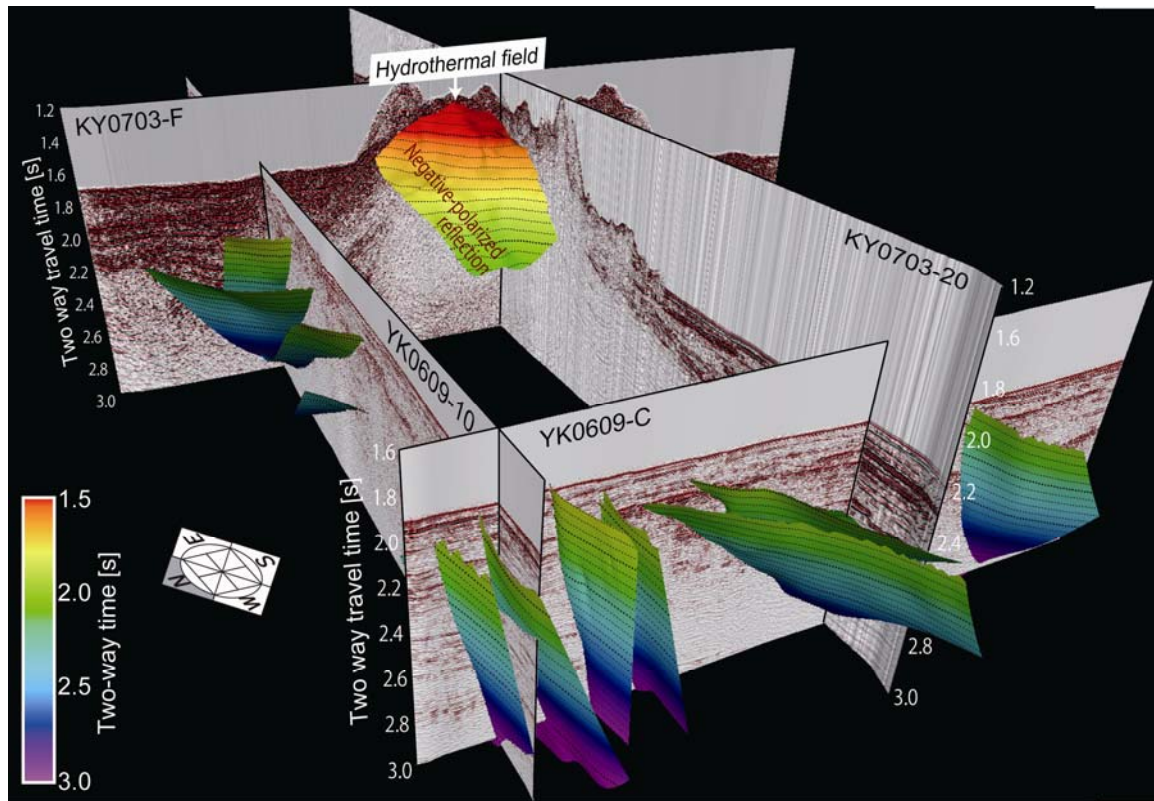
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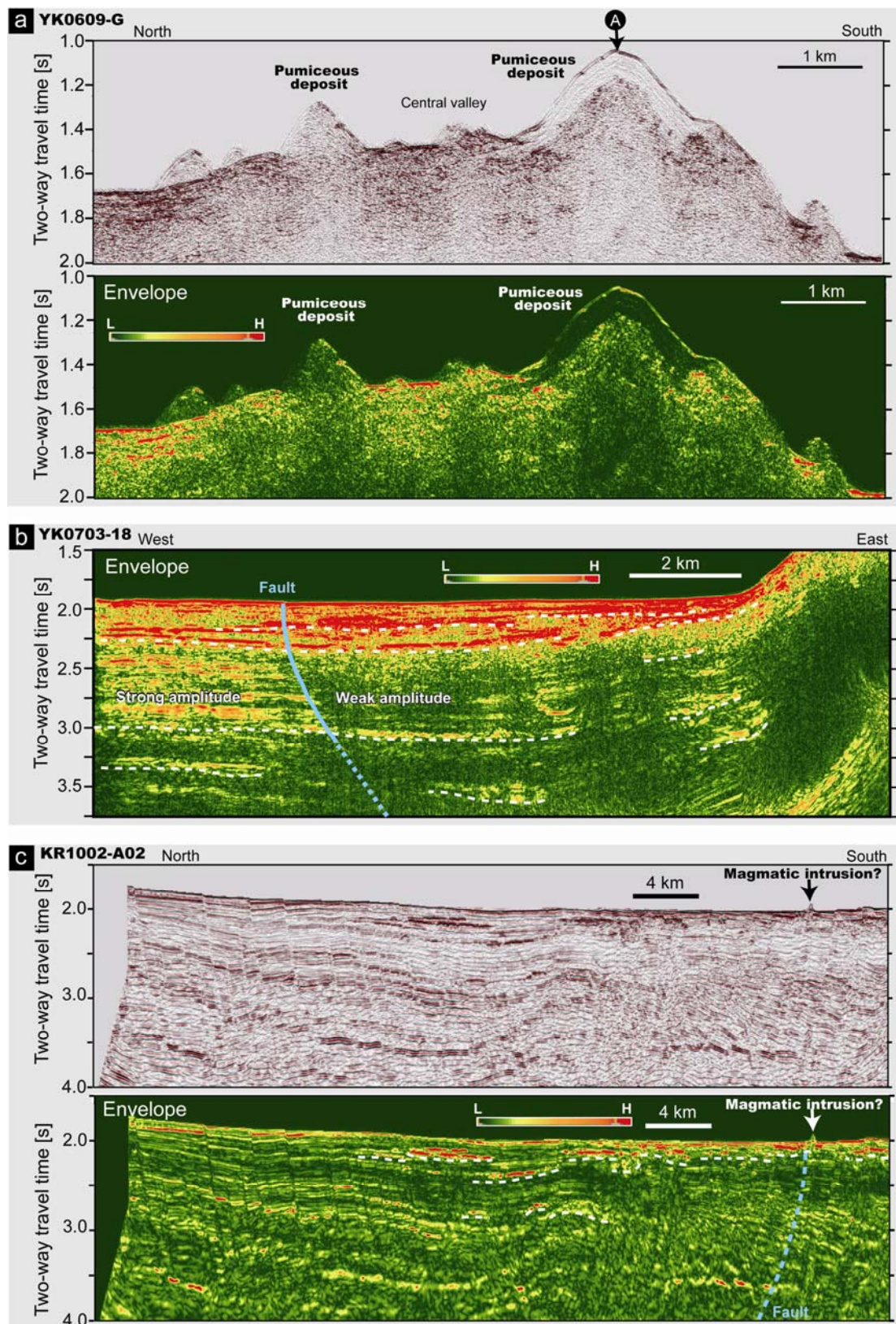
## Hydrothermal fluid paths in continental margin



**Figure 6.** Fence diagram showing a 3D view of the seismic profiles and the geometry of the negative-polarity reflector and faults within trough-fill sediments. The shallowest part of the subseafloor negative-polarity reflection (top of low-velocity sequence) corresponds to the location of the hydrothermal field (white arrow). The faults displayed here were interpreted from intersecting orthogonal 2D profiles.



## Hydrothermal fluid paths in continental margin



**Figure 7.** (a) N–S seismic profile (line YK0609-G2) crossing the central valley

## Hydrothermal fluid paths in continental margin

582 east of the hydrothermal field showing volcanic pumice deposits (upper), and  
583 amplitude envelope profile (lower) used to identify volcanic deposits within the  
584 sedimentary sequence. Locations of the seismic profiles are shown in Figure 1c.  
585 (b) Amplitude envelope profile of line KY0703-18. This profile is an enlargement  
586 from Figure 5a showing interpreted volcanic deposits (white dashed lines).  
587 Volcanic rocks within the sedimentary sequence are represented by  
588 high-amplitude, low-frequency reflections. (c) N–S seismic profile west of the  
589 Iheya North Knoll and amplitude envelope profile with interpreted volcanic  
590 deposits (white dashed lines).

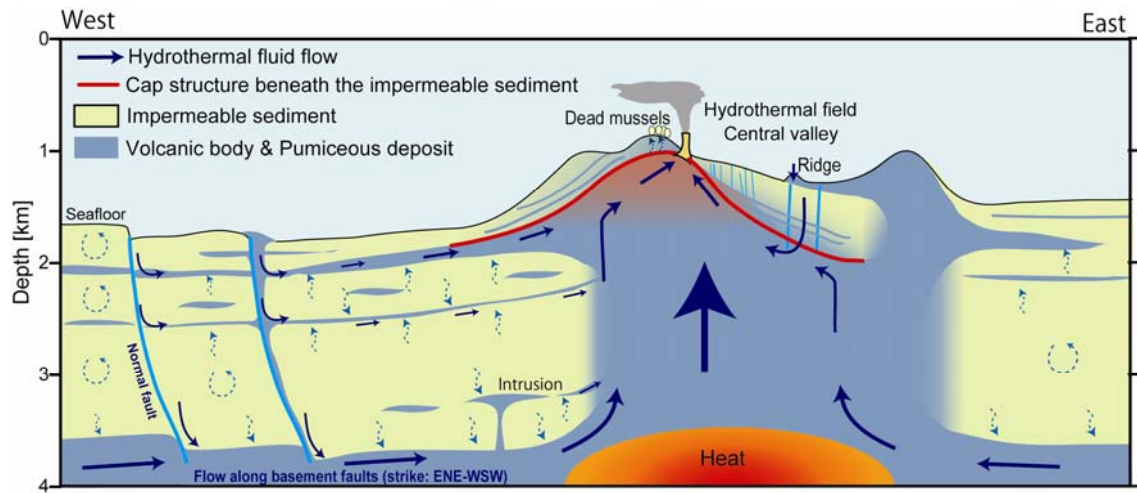
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## Hydrothermal fluid paths in continental margin



**Figure 8.** Model of the hydrothermal fluid system around the Iheya North Knoll (based on seismic profile KR1002-18; Fig. 3a). Fluids flow laterally and updip along permeable pumiceous layers within the sedimentary sequence and laterally along basement faults within the crust. Near the knoll, fluids migrate upward due to heating and are then trapped below the hydrogeologic barrier (red line) and flow beneath it to vents in the hydrothermal field.